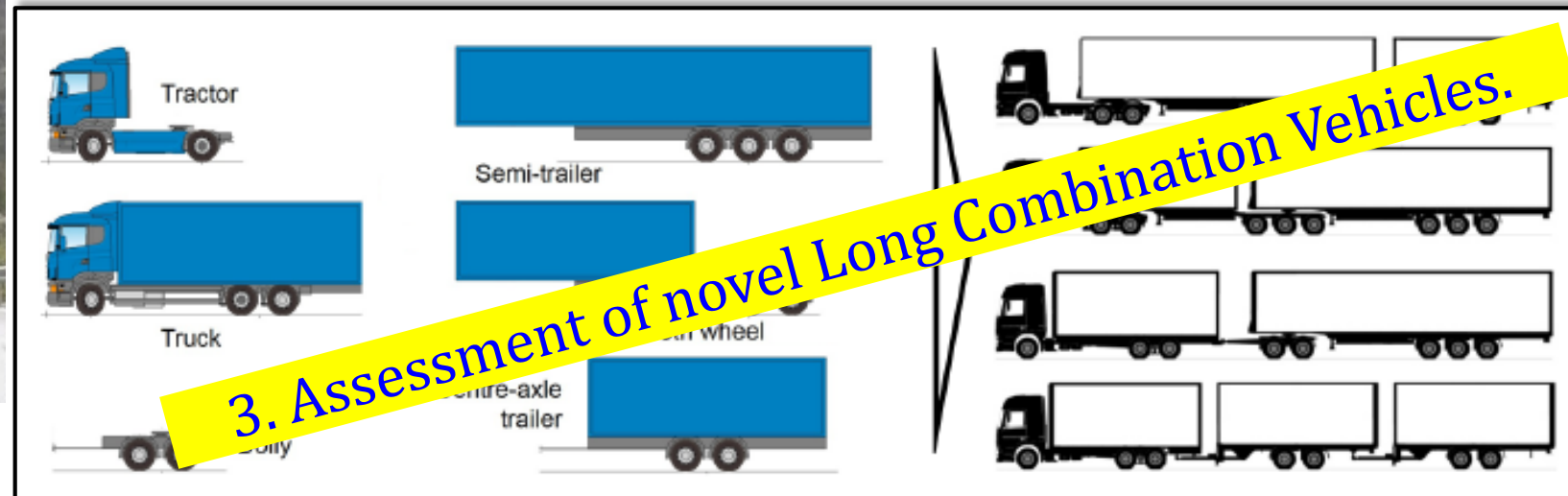
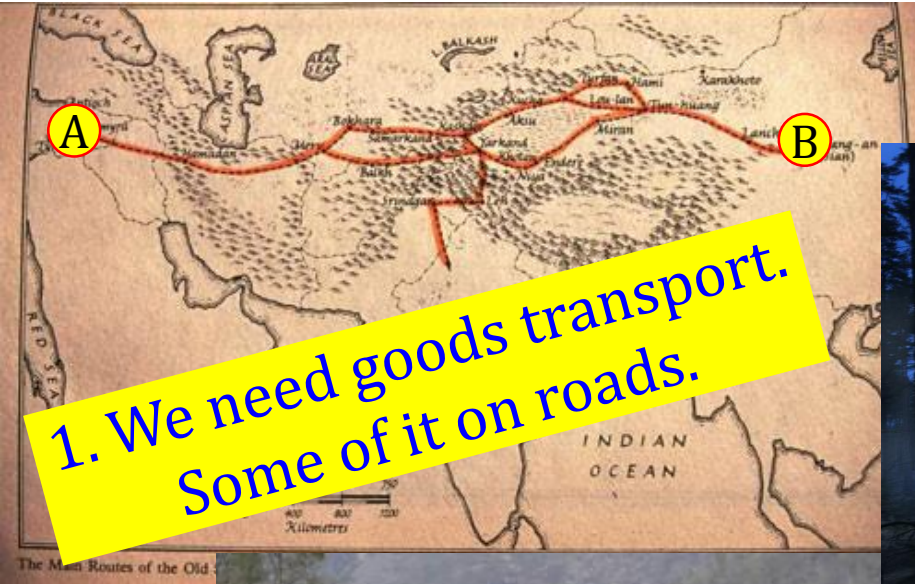




# **Assessment methods of High Capacity Transports**

**Bengt Jacobson, Vehicle Dynamics,  
Chalmers University of Technology, Göteborg, Sweden**

# Why & How High Capacity Transports





# My present involvement in Assessment of HCT

<https://research.chalmers.se/en/project/8350>

project: **Performance Based Standards 2, PBS2**, 2018-2020



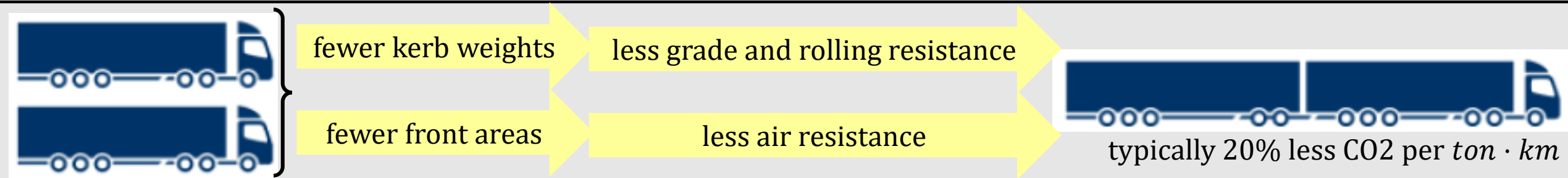
- **Chalmers University of Technology**, Gothenburg, Sweden
- **Nokian Tyres**, Finland
- **Parator Industri**, Bollnäs, Sweden
- **Scania**, Södertälje, Sweden
- **Swedish Transport Administration**, Borlänge, Sweden
- **Swedish Transport Agency**, Norrköping, Sweden
- **Swedish National Road and Transport Research Institute (VTI)**, Linköping, Sweden
- **University of Oulu**, Oulu, Finland
- **Volvo Group**, Gothenburg, Sweden



- |   |
|---|
| WP1 –Tire Modelling.....                                    |
| WP2 –Heavy vehicle experiments.....                         |
| WP3 – Road network categorization.....                      |
| WP4 – Simulations.....                                      |
| <b>WP5 – PBS Assessment..</b> .....                         |
| WP6 – International cooperation and knowledge spreading ... |
| WP7 – Project management .....                              |

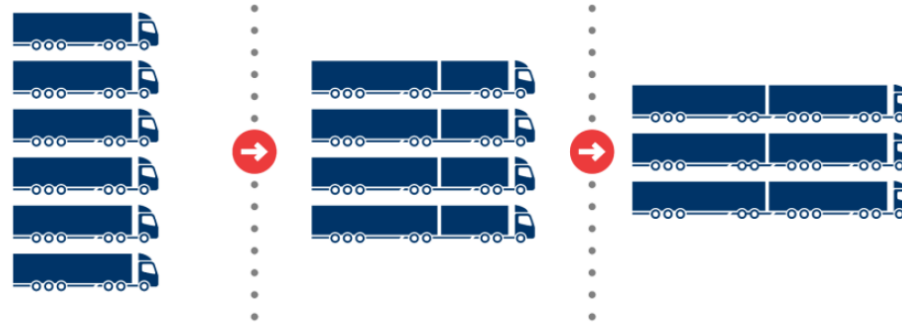
# How can HCT save CO<sub>2</sub>?

$$\boxed{m} \cdot \dot{v} = F_{prop} + F_{brk} - \boxed{m} \cdot g \cdot RRC + \boxed{m} \cdot g \cdot \varphi_{grade} - \frac{\rho \boxed{A} \cdot c_d}{2} \cdot v^2; \quad \text{where } m = m_{kerb} + m_{load};$$



## TRANSPORTATION OF 600 M<sup>3</sup> OF VOLUME LIMITED GOODS WITH THE SAME DENSITY (150KG/M<sup>3</sup>)

...and even more reduction of CO<sub>2</sub> per m<sup>3</sup> · km:



Vehicles (and drivers)	6	4	3
Vehicle length	16.5 m	25.25 m	32 m
Load per vehicle	100 m <sup>3</sup>	150 m <sup>3</sup>	200 m <sup>3</sup>
Fuel consumption	3.5 ml/m <sup>3</sup> km	3 ml/m <sup>3</sup> km	2.5 ml/m <sup>3</sup> km
CO <sub>2</sub> emissions	100%	85% = -15%	73% = -27%
Road use	499 m	368 m	296 m

Source: Cider L, Larsson L, HCT DUO2-project Gothenburg-Malmö in Sweden, 2019

# Special HCT assessment? What “(Traffic) Risks” do we see?

Today: Each vehicle **unit** separately approved. Automatically OK to couple some, e.g. one Tractor + one SemiTrailer.



So, what can be “risks” when combining more of approved units?



## Traffic Flow

- *Stuck in uphill*  $\Rightarrow$  Startability
- *Slow in uphill*  $\Rightarrow$  Gradeability
- *Slow on entry/exit roads*  $\Rightarrow$  Acceleration Capability)
- ... $\Rightarrow$  Low Speed Swept Path
- ... $\Rightarrow$  Frontal Swing
- ... $\Rightarrow$  Tail Swing
- ... $\Rightarrow$  Friction demand on Drive Tyres
- ... $\Rightarrow$  Friction demand on Steering Tyres
- ... $\Rightarrow$  Tracking Ability on a Straight Path

## Traffic Safety

- ... $\Rightarrow$  High Speed Steady State Off Tracking
- ... $\Rightarrow$  Steady State Rollover Threshold
- ... $\Rightarrow$  Load Transfer Ratio
- ... $\Rightarrow$  High Speed Transient Off Tracking
- ... $\Rightarrow$  Yaw Damping
- ... $\Rightarrow$  Rearward Amplification
- ... $\Rightarrow$  Braking Stability in a Turn
- ... $\Rightarrow$  Coupling Forces

Each bullet is “*Traffic Risk*  $\Rightarrow$  PBS”.

Each PBS is motivated by one Traffic Risk, which we think is **not** handled by approval of the single units.

We strictly define one (PBS) **measure** for each risk and set a numerical min/max **requirement**.



# **Different assessment methods and PBS**



# How can we assess HCT?

**PBS** (for all PBSes:

*Measures<sub>i</sub> > Requirement<sub>i</sub>*):

- Strict agreements on measures
- Real vehicle test
  - Expensive, poor repeatability, difficult to vary operation parameters, such as road friction
- or Virtual test (computation, simulation)
  - Authorized “assessors” with their own models
    - or Anyone compute with agreed open models
  - How to get parameter values?

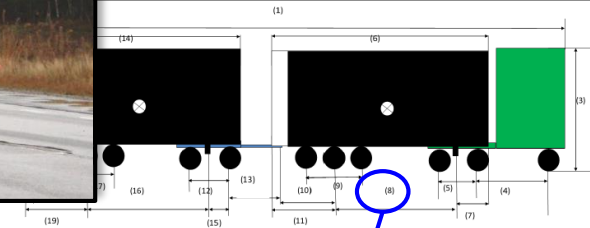


Figure 6.22: A-Double : Description and Dimensions

Table 6.6: Dimensional limit chart for A-double

Vehicle	Ref	Feature	Dimensions(Sweden)	Dimensions(Canada)
Overall	(1)	Length of the combination	Max 34m	Max 40 m
	(2)	Width of Vehicle	Max 2.6m	Max 2.6 m
	(3)	Height of the Vehicle	-	Max 4.15 m
Tractor	(4)	Wheelbase	3.0 - 3.8 m	Min 3.5 m
	(5)	Tandem axle spread	1.37 m	1.2 - 1.85 m
Lead Semi-trailer	(6)	Length	13.6 m	14.5 - 16.2 m
	(7)	Front Over-hang	1.6 m	Max 2 m
	(8)	Wheelbase	7.7 - 8.5 m	10.9 - 12.5 m
	(9)	Rear Over-hang	3.5 - 4.3 m	Max 3.4 m
Converter Dolly	(12)	Wheelbase	1.3 m	1.2 - 1.85 m
	(13)	Drawbar length	3.0 - 5.0 m	Max 3m
1 Semi-trailer	(14)	Length	13.6 m	14.5 - 16.2 m
	(15)	Front Over-hang	1.6 m	Max 2 m
	(16)	Wheelbase	7.7 - 8.5 m	10.2 - 12.5 m
	(17)	Tridem axle spread	2.6 m	2.4 - 3.7 m
	(18)	Distance to hinge point	2.4 - 3.6 m	-
	(19)	Rear Over-hang	3.5 - 4.3 m	35% of wheelbase

**Prescriptive:**

- “Blue prints”
- Envelops in table format

**Statistics from real use:**

- Assess each Individual vehicle
- Assess each Transport operator

**Warning: An assessment method can reduce incentive for technology developments!**

**Lead-Semi-trailer: Wheelbase: 7.7-8.5 m**

**January 2019**, Finland allows: **34,5 m 76 ton**, on whole road network, except some bridges and intersection.  
Assessed by test and simulation. Using regression  $\Rightarrow$  "PBS-based envelope-table".

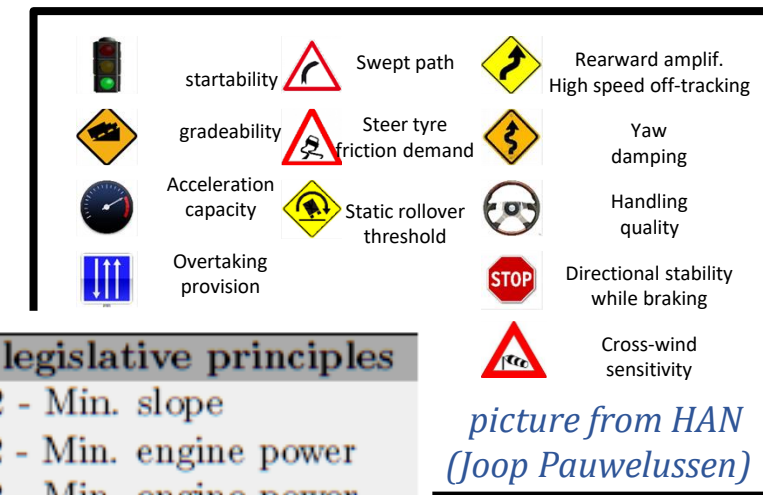


Semi-trailer wheel-base	Full trailer wheel-base	Coupling under hang	Coupling from the bogie	Yaw rate rearward amplification [RA]				
				Drawbar length				
				3500	3750	4000	4250	4500
8108	8108	200	2592	2.36	2.35	2.33	2.31	2.29
		400	2392	2.33	2.32	2.30	2.28	2.26
		600	2192	2.29	2.28	2.26	2.25	2.22
		800	1992	2.26	2.25	2.23	2.21	2.19
	8282	200	2592	2.30	2.29	2.27	2.25	2.23
		400	2392	2.27	2.25	2.24	2.22	2.20
		600	2192	2.23	2.22	2.20	2.19	2.16
		800	1992	2.20	2.19	2.17	2.15	2.13
	8457	200	2592	2.24	2.23	2.21	2.19	2.17
		400	2392	2.21	2.20	2.18	2.16	2.14
		600	2192	2.18	2.16	2.15	2.13	2.11
		800	1992	2.14	2.13	2.12	2.10	2.08
	8631	200	2592	2.19	2.17	2.16	2.14	2.12
		400	2392	2.15	2.14	2.13	2.11	2.09
		600	2192	2.12	2.11	2.10	2.08	2.06
		800	1992	2.09	2.08	2.06	2.05	2.03
	8805	200	2592	2.13	2.12	2.11	2.09	2.07
		400	2392	2.10	2.09	2.08	2.06	2.04
		600	2192	2.07	2.06	2.05	2.03	2.01
		800	1992	2.04	2.03	2.02	2.00	1.98
	8980	200	2592	2.08	2.07	2.06	2.04	2.02
		400	2392	2.06	2.04	2.03	2.01	1.99
		600	2192	2.03	2.01	2.00	1.98	1.96
		800	1992	2.00	1.99	1.97	1.95	1.93
	9154	200	2592	2.04	2.02	2.01	1.99	1.97
		400	2392	2.01	2.00	1.98	1.97	1.95
		600	2192	1.98	1.97	1.96	1.94	1.92
		800	1992	1.95	1.94	1.93	1.91	1.89
High rearward amplification, RA > 2								
Open-loop lane change test according to ISO 14791 f = 0.40 Hz ja v = 80 km/h								



# EU

from Karel Kural, PhD thesis:



No.	Australian PBS Measure	Current EU-Legislation	Proposed EU legislative principles
1	Startability	R No 1230/2012 - Min. slope	R No 1230/2012 - Min. slope
2	Gradeability	R No 1230/2012 - Min. engine power	R No 1230/2012 - Min. engine power
3	Acceleration capability	R No 1230/2012 - Min. engine power	R No 1230/2012 - Min. engine power
4	Tracking ability	N/A	N/A
5	Directional braking stability	R No 661/2009 - Braking stability	R No 661/2009 - Braking stability
6	Overtaking provision	N/A	N/A
7	Low-speed swept path width	D 97/27 EC - Max. swept area	D 97/27 EC - Max. swept area
8	Steer tyre friction demand	R No 1230/2012 - Min. steer axle load	R No 1230/2012 - Min. steer axle load
9	Frontal swing	N/A	Use Australian definition
10	Tail swing	D 97/27 EC - Tail swing	D 97/27 EC - Max. tail swing
11	Static rollover threshold	N/A	Use Australian definition
12	Rearward amplification	N/A	Use Australian definition
13	Yaw damping	N/A	Use Australian definition
14	Load transfer ratio	N/A	Use New Zealand definition
15	High-speed transient offtracking	N/A	Use Australian definition
16	Handling quality	N/A	N/A
17	Pavement vertical loading	D 96/53/EC - Max. axle load	D 96/53/EC - Max. axle load
18	Pavement horizontal loading	D 96/53/EC - Axle spacing vs. load	D 96/53/EC - Axle spacing vs. load
19	Tyre contact pressure distribution	D 96/53/EC - Air suspension required	D 96/53/EC - Air suspension required
20	Bridge formulae	N/A	N/A

Table 2.11: Comparison of EU legislation with Australian legislation and proposal for future legislative principles.

# LastBilsKalkylatorn LBK <https://lastbils kalkylator.azurewebsites.net>

Sweden introduced a web service (LBK) to assess individual **combination vehicles** when for 64 ton was allowed 2018. (Actually assesses individual “transport **operations**”, since  $F_z$  per axle is input.)

lastbils kalkylator.azurewebsites.net

**TRANSPORT STYRELSEN**


## Lastbils kalkylator

**Frågor och svar**  
Se vanliga frågor och svar om lastbils kalkylatorn.

**I den här tjänsten kan du få en bedömning om en fordonskombinations kopplingsutrustning, och även en bedömning om de prestandakrav som gäller för fordonskombinationer är över 64-ton.**

OBS! Det är förarens/användarens ansvar att kontrollera att de data som används för beräkningarna är korrekta.

Börja med att ange registreringsnumren för de fordon som ska ingå i ekipaget (mellan 2 och 3 fordon). Saknas tekniska data för dina fordon kan du komplettera med detta.



Fordon Tekniska data Last Resultat

Steg 1 av 4

Första fordonet

Lastbil

Registreringsnummer (valfritt)

DZK447

Fordonstyp

Lastbil

Andra fordonet

Dolly

Registreringsnummer (valfritt)

DZM444

Fordonstyp

Dolly

Tredje fordonet

Påhängsvagn

Registreringsnummer (valfritt)

RCS736

Fordonstyp

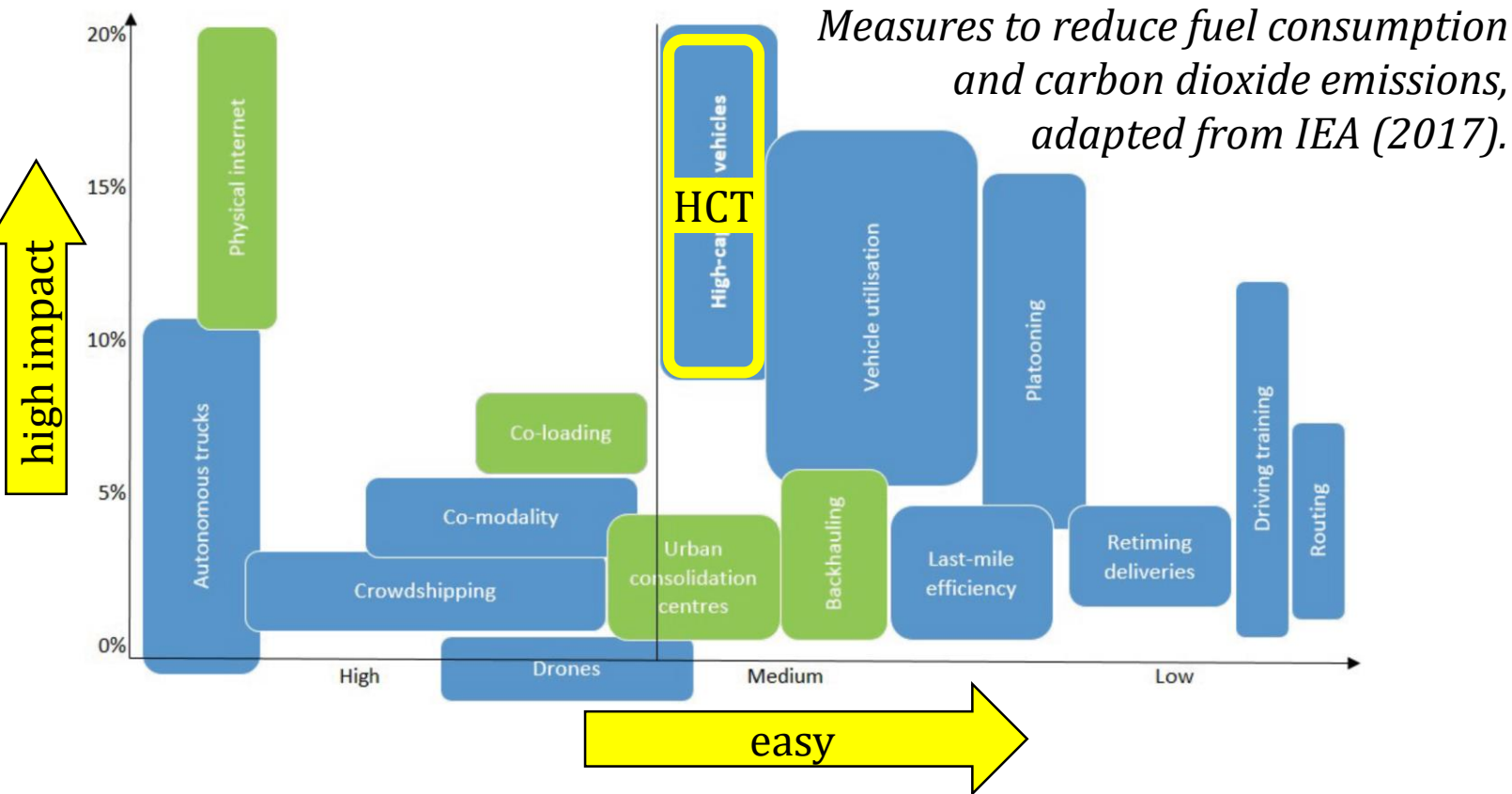
Påhängsvagn

Nästa

input registration numbers of the units in order first to last

## Lastbils kalkylator

# CLOSER <https://closer.lindholmen.se/en>



The overall goal for **2030** is to provide the conditions so that **80%** of the freight transport work on the road is carried out by HCT vehicles (the targets for **2020** are **5%** and for **2025** **45%**) and that this means that energy consumption will be **10%** lower per tonne meter than 2018

Innovationsdomän	Tidshorisont	Delmål	Ansvarig aktör	Barriärer
PBS	2025	Lastbils kalkylatorn har kompletterats med PBS-baserat krav för längre HCT-fordon.	Transportstyrelsen, forskningsinstitut	
PBS	2030	Ett europeiskt system för SIAP "Smart Infrastructure Access Policy" finns vilket innebär optimering av matchningen fordon & infrastruktur	Transportstyrelsen, forskningsaktörer	Brist inom finansiering samt samarbete mellan involverade intressenter.
Regelverk	2030	Ett globalt regelverk finns på plats för att certifiera hårdvara, mjukvara och processer för uppkopplade fordon och alla tillhörande back-end och molnsystem.	Regeringar	Särintressen

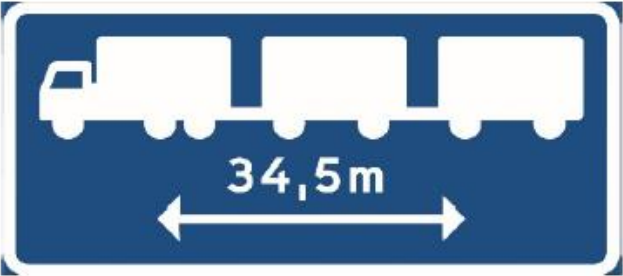
**LBK<sup>+</sup>**



# Presently on remittance in Sweden

[https://www.trafikverket.se/contentassets/1160ae4fe6504bba8e3629eee4b60d7c/langre\\_lastbilar\\_pa\\_det\\_svenska\\_vagnatet\\_for\\_mer\\_hallbara\\_transporter.pdf](https://www.trafikverket.se/contentassets/1160ae4fe6504bba8e3629eee4b60d7c/langre_lastbilar_pa_det_svenska_vagnatet_for_mer_hallbara_transporter.pdf)

Vägmärke: F31.a Färdväg för långa fordonståg



Tabell 1. Resultat från förenklad samhällsekonomisk beräkning.

Effektkategori	Samhälls-ekonomisk effekt	Effekt tidigare studie	Resultat, mkr	Känslighets-analys högt marknads-upptag, mkr	Känslighets-analys lågt marknads-upptag, mkr
Producent-/ konsumenteffekter	Fordons-ägare eller godstransport-köpare	177 963	12 916	15 499	10 333
Budgeteffekter	Dieselskatt	-30 733	-2 231	-2 677	-1 784
Externa effekter	Road wear	2 910	211	253	169
	Air pollution	538	39	47	31
	CO2	8 382	608	730	487
	Accidents	3 040	221	265	177
	Transport time	835	61	73	48
	Totalt	162 935	11 825	14 190	9 460

≈ 10<sup>9</sup>€

# LBK<sup>+</sup> $\approx$ OpenPBS <http://192.36.94.52:8000/>

PBS2 project extends the LBK to longer than 24.5 m.

The initiative is called OpenPBS and has 2 front-ends:

- An “**assessment front-end**” with a simple user interface as in present LBK
- An “**R&D front-end**”, enabling download and editing of models (change any parameters, add equations and parameters to try e.g. extra propelled and steered axles).

Both front-ends are using the same dynamic models on the open format Modelica (<https://modelica.org/>)

Present experiment implementation of the “Assessment front-end”

## OpenPBS Calculator

**Registration Numbers**  
BA1  
DC1  
DA1  
BA2  
DA1  
**Add**

**Vehicle Combination**  
BA1  
DC1  
DA1  
**Remove** **ClearAll** **Run**

A small “road vehicle register” (10-20 real units, fake reg numbers)

### Simulation Results

RegNrs:['BA1', 'DC1', 'DA1']  
CombType:NordicCombination  
G:0.0491331598071045  
TASP:0.0809952967524567  
RWA:1.486201503236101  
YD:0.1689152468799537  
RWA:-1.0  
YD:-1.0

Computed PBS measures

### List of Parameters

Name	Value
nu:	3
na:	4
L:	[0.0, -4.1, -5.449999999999999, -6.749999999999999; 0.0, -1.3, 0.0, 0.0; 0.0, -1.32, -2.64, 0.0]
w:	[2.115, 1.84, 1.84, 2.115; 2.245, 2.245, 0.0, 0.0; 2.235, 2.235, 2.235, 0.0]
axlegroups:	[1, 2, 2, 2; 1, 1, 0, 0; 1, 1, 1, 0]
A:	{0.0, 2.9800000000000004, 6.83}
B:	{-8.225, -0.65, -5.17}
driven:	[false, true, true, true; false, false, false, false; false, false, false, false]
Cc:	[7.5, 7.5, 7.5, 7.5; 7.5, 7.5, 0.0, 0.0; 7.5, 7.5, 7.5, 0.0]
m:	{32000.0, 2360.0, 36420.0}
X:	{-4.442265624999999, -0.10518672199170125, 0.7822820565623284}
I:	{165879.14988606767, 2360.0, 441386.97080787766}
ROH:	{-8.899999999999999, -1.9700000000000002, -5.17}
FOH:	{1.4500000000000001, 3.0799999999999996, 8.46}
cgh:	{2.013640625, 0.5073550847457626, 2.3606473852507777}

# So, whats the problem???

## Definition of PBSeS:

- ISO gives several selections and can be interpreted differently.
- Who agree and How?
- What more than PBSeS is needed

e.g.

- Rearward amplification  $RA$  ratio of  $\omega_z$  or  $a_y$ ?
- and  $RA = \frac{\max_t(|\omega_{iz}|)}{\max_t(|\omega_{1z}|)}$  or  $\max_f \left( \frac{|H_{\delta_{SW} \rightarrow \omega_{iz}}(f)|}{|H_{\delta_{SW} \rightarrow \omega_{1z}}(f)|} \right)$ ?
- and is manoeuvre single sine (what  $\Delta x$ ? what  $\Delta y$ ?) or single lane change (what  $\Delta x$ ? what  $\Delta y$ ?)
- and what speed  $v_x$ ? and what road friction  $\mu$ ?

Proposal: First agree on which “risks”

e.g. clash between unit bodies

## Model (equations):

- How detailed is necessary?  
How simple is possible?

e.g. is roll important? is xy-planar motion enough?

See: Santahuhta, thesis from University of Oulu, Finland, 2019.

## Parameters (numeric values) :

- The vehicle registry does not include all parameters.

- e.g. suspension data, engine map, gear ratios, ...
- e.g. cornering coefficient=7.5 [N/N]?, ...
- e.g. should operator/driver input  $F_z$  per axle or compute from max allowed gross weight and assumed CoG location

*Consider: An assessment method can remove incentive for technology developments*

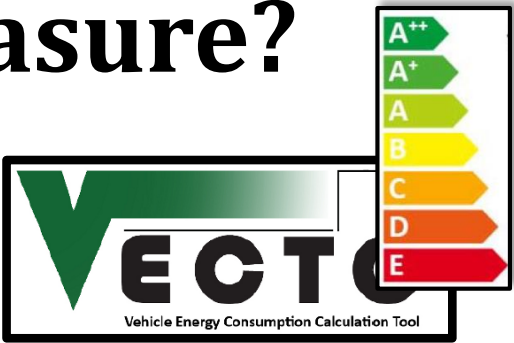
- e.g. steered axle on towed units
- e.g. control algorithm (IP!), ...



# Could CO<sub>2</sub> be a PBS measure?



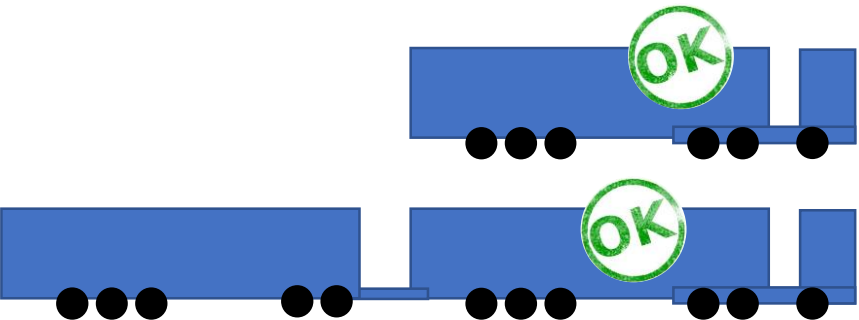
Euro1, Euro2, ...  
Legal assessment  
of **engines**



Vecto  
Rating of  
**towing  
vehicles**



Vecto can also become tool  
for next legal assessment  
of **towing vehicles**



CO<sub>2</sub> a future “PBS measure”?  
I.e., per **vehicle** (not per unit)?



...or per  
**operation?**

from Karel Kural, PhD thesis:

No.	Societal Benefit Measure	Units
1	Carbon dioxide pollution - load-wise	CO <sub>2</sub> /ton.km
2	Carbon dioxide pollution - volume-wise	CO <sub>2</sub> /m <sup>3</sup> .km
3	Fuel consumption - Load-wise	l/ton.km
4	Fuel consumption - Volume-wise	l/m <sup>3</sup> .km
5	Transport costs - Load-wise	€/ton.km
6	Transport costs - Volume-wise	€/m <sup>3</sup> .km

Table 2.12: Proposed societal benefit measures for future regulations

The background image is a landscape photograph. The top half shows a clear, light blue sky with a single, bright, circular sun or moon positioned slightly to the right of the center. The bottom half shows a calm body of water reflecting the light from the sun/moon. In the foreground, there is a rocky shoreline with several large, dark rocks. The overall color palette is dominated by blues and greys, with a warm yellow/white light source.

# Design principles of “Open PBS”

# Envisioned solution and top level Requirements on it

## *An Open PBS Tool*

*(Open means: Free and Readable and Understandable)*

### **Requirements:**

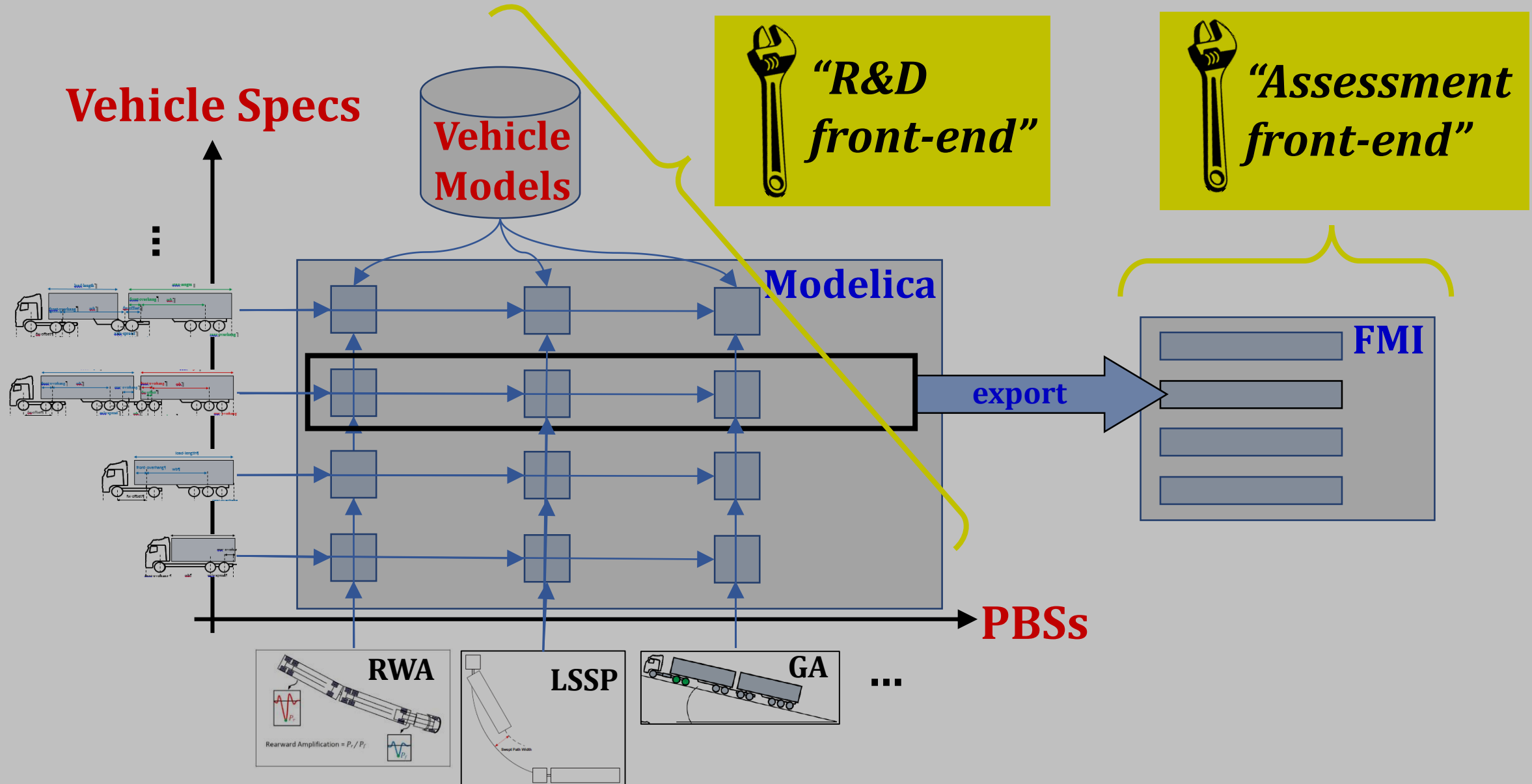
- PBSs independent of Vehicles
- Vehicles specifications (“parameters”) independent of Vehicle models (“equations”)
- Standardized format for dynamic models



# Requirements on $\Rightarrow$ Concepts for an “Open PBS Tool”

Requirements	Conceptual solutions
Define these 3 independently from each other: <ul style="list-style-type: none"><li>• PBSs (Manoeuvres &amp; Measures)   (“equations &amp; parameters”)</li><li>• Vehicle Specs (“parameters”)</li><li>• Vehicle Models (“equations”)</li></ul>	Object oriented modelling
<b>Physical</b> and <b>strict</b> models (for adding novelties)	DAE
<b>Understandable</b> and <b>editable</b> for engineers	Modelica $\Rightarrow$ <i>R&amp;D front-end</i>
<b>Runnable</b> for non-experts. <b>Scriptable</b> for experts.	FMI $\Rightarrow$ <i>Assessment front-end</i>
<b>Limited parameter editable</b> for non-experts. (In extreme: Only registration number on each of the units.)	Modelica concepts Registry and Function

# Two tools in one...

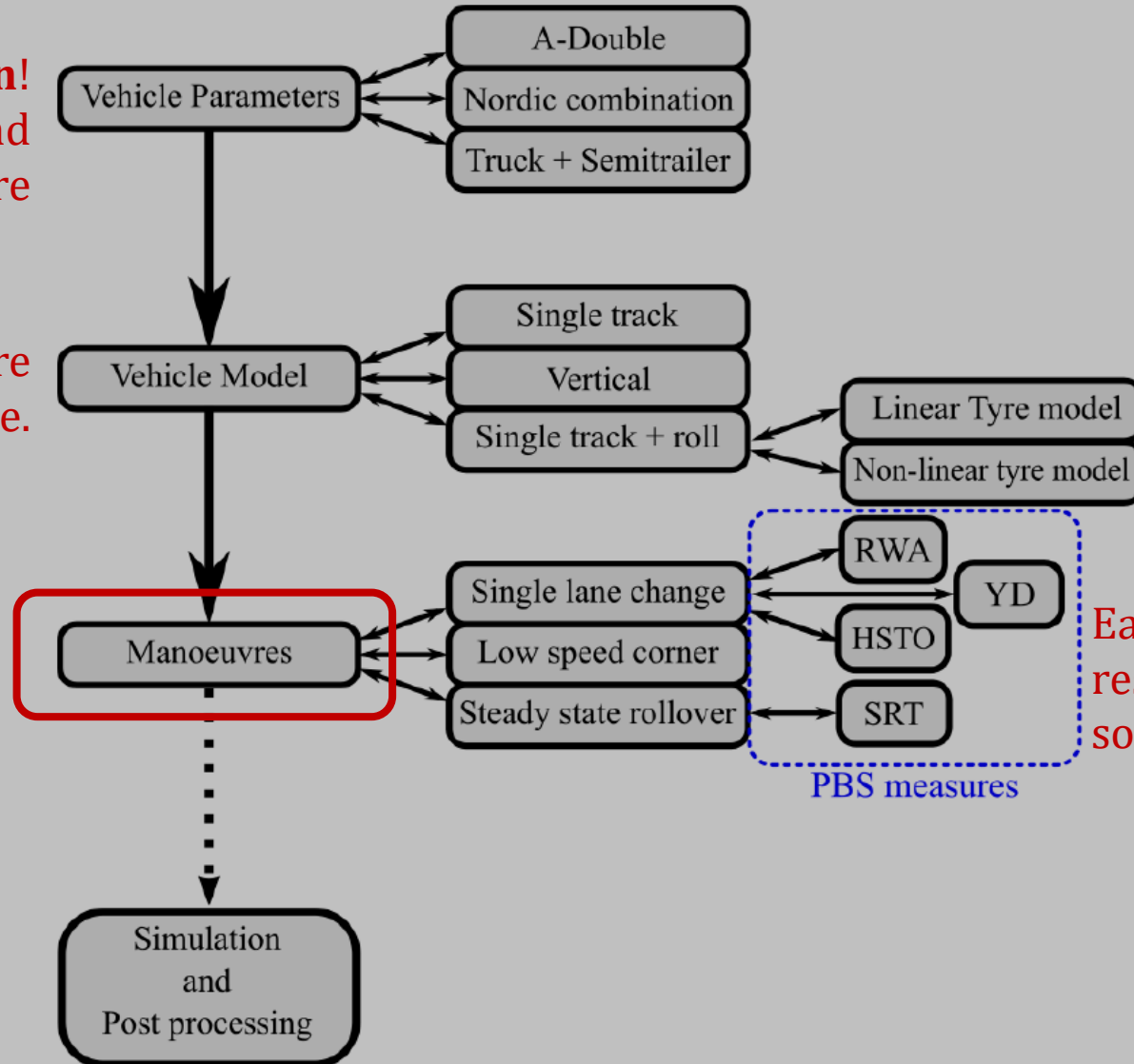


# Concepts selected

Here is the **parameterisation!**  
Independent from model and  
manoeuvre

Vectorized models are  
used as far as possible.

**Manoeuvres** are the  
“simulatable models”.

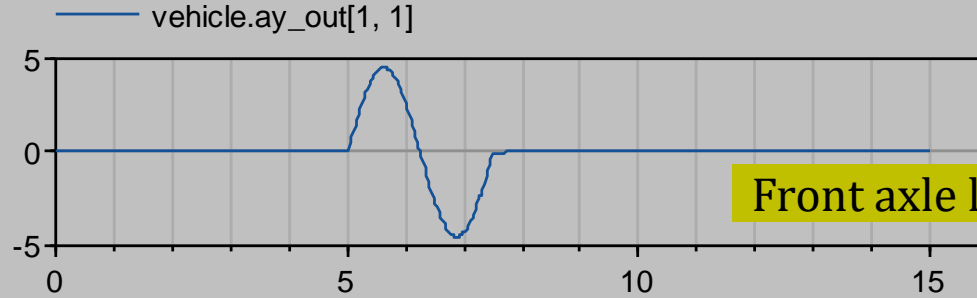


Each manoeuvre is  
responsible to compute  
some of the **PBSes**.

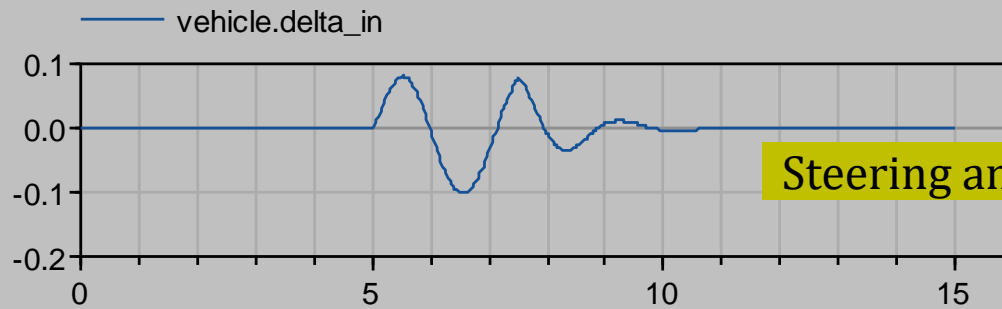
Figure 2. Overview of how OpenPBS is structured.



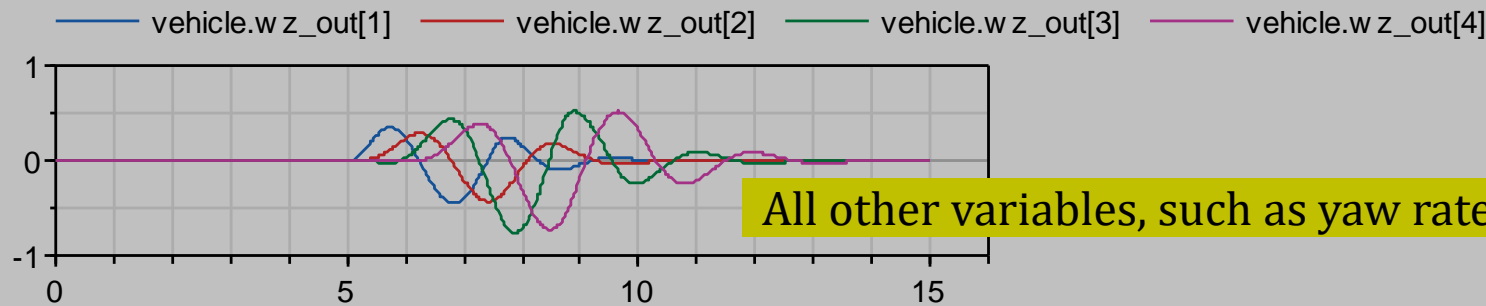
# Example: Manoeuvre “High Speed Lane Change”



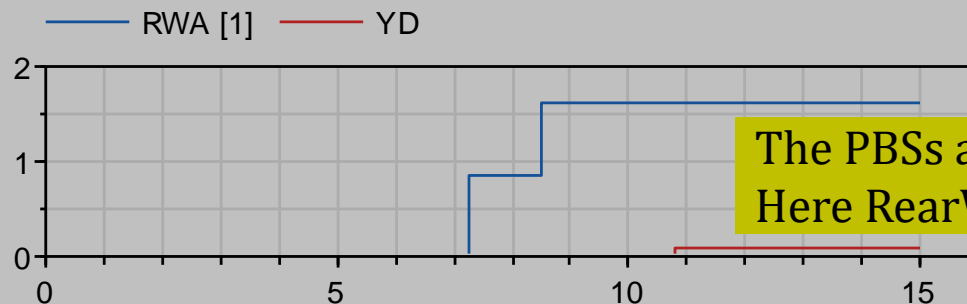
Front axle lateral acceleration is prescribed to exact sinus path



Steering angle is computed (but not of primary interest)



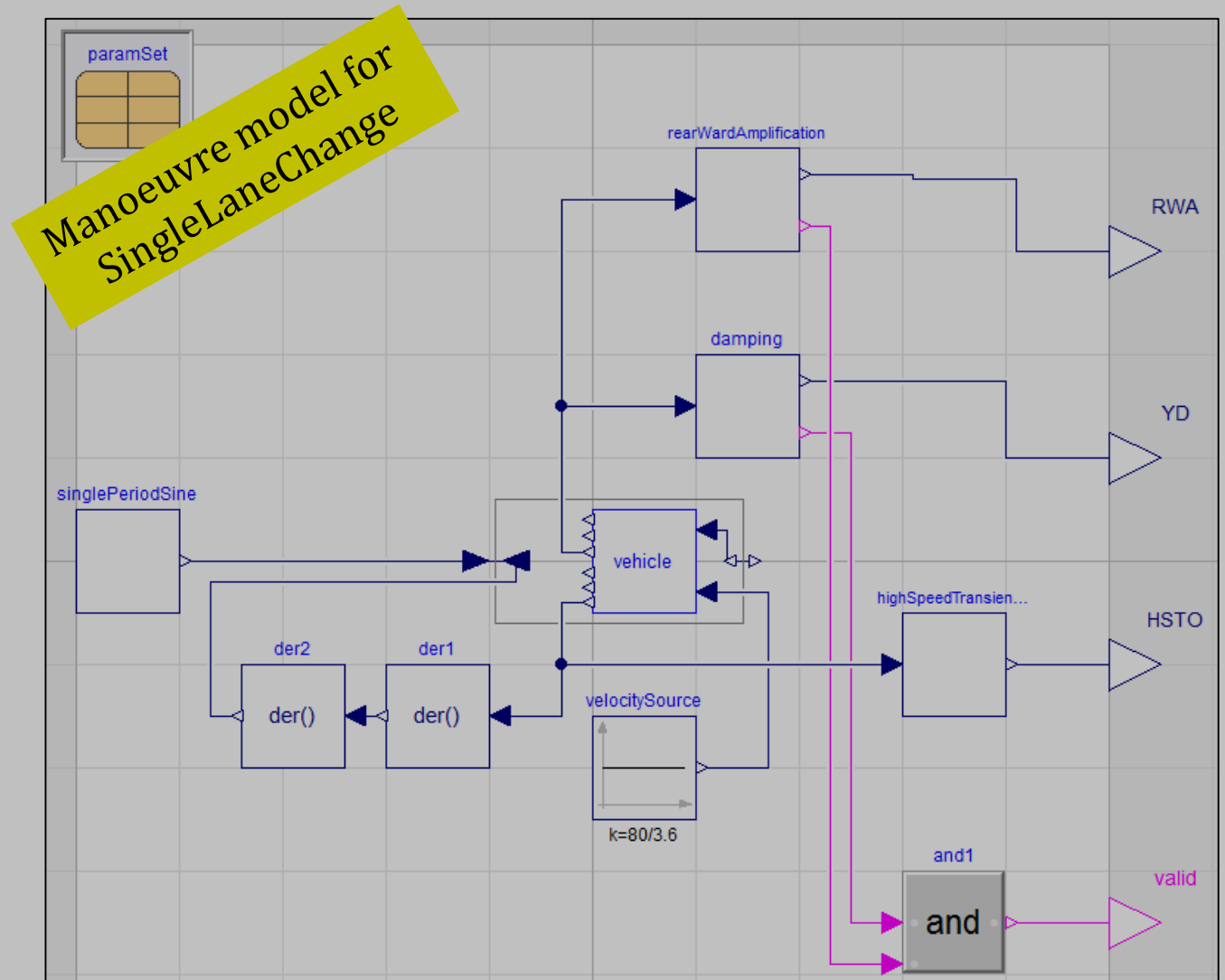
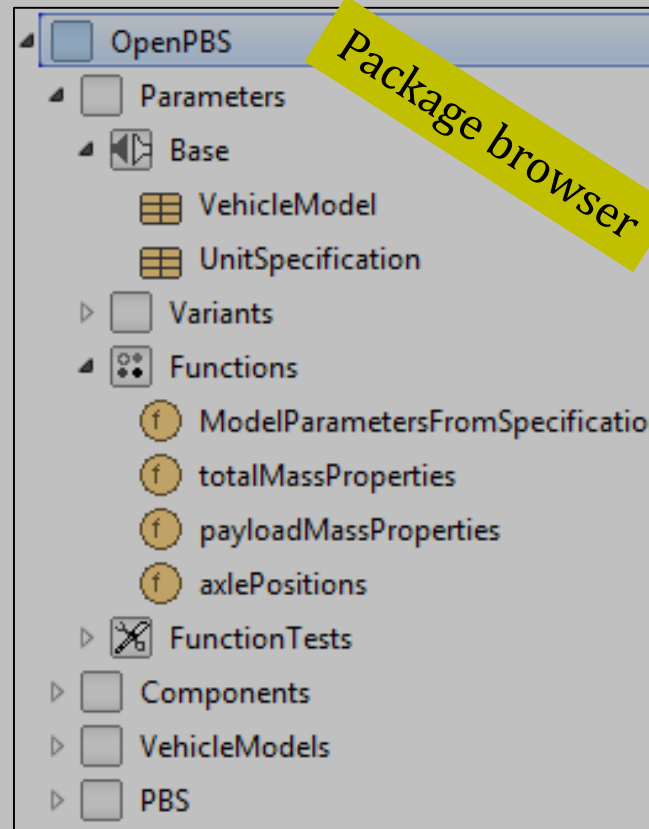
All other variables, such as yaw rates are, of course, also computed



The PBSs associated with this manoeuvre is calculated.  
Here RearWardAmplification (RWA) and YawDamping (YD)

# How does "R&D tool" look?

The "R&D tool" is a Modelica "package" (\* .mo).  
Here opened in the Modelica tool "Dymola":

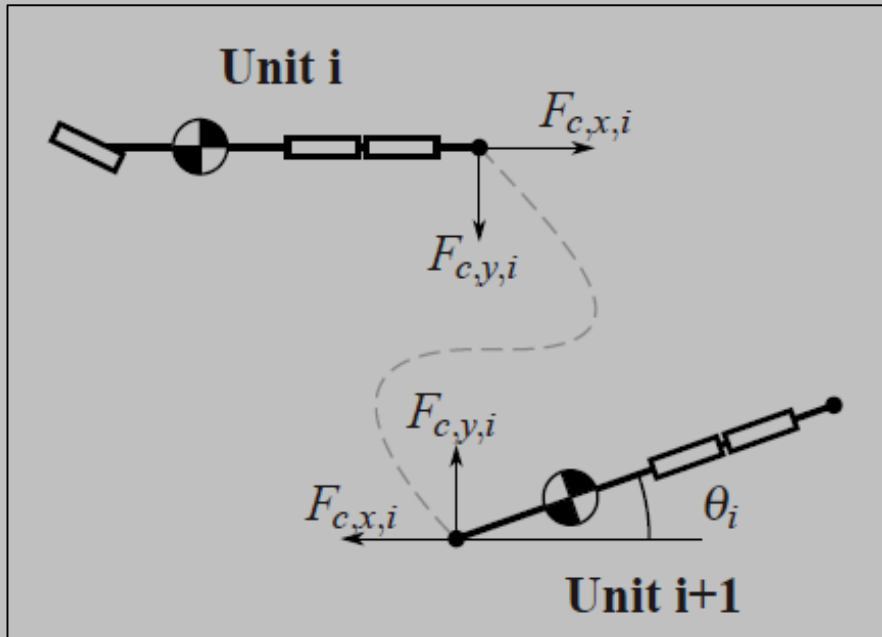


# How does a “Vectorised VehicleModel” look?

Here, Vectorised Lateral Dynamics VehicleModel:

≈1 page declarations

≈1 page equations



## (Dynamic) Equilibria:

```
ay=der(vy)+vx.*wz;  
m.*ay=Fy*ones(na,1)-[Fcy;0]  
+[0;Fcx].*sin([0;theta])  
+[0;Fcy].*cos([0;theta]);
```

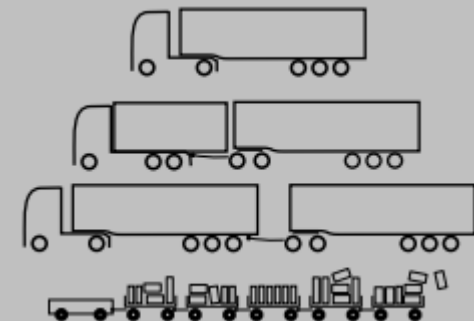
## Constitution:

```
Fyw = -C.*alpha;
```

## Compatibility:

```
for i in 1:nu-1 loop  
vx[i+1] = vx[i]*cos(theta[i])  
        -(vy[i]+Bcog[i]*wz[i])*sin(theta[i]);  
vy[i+1]+Acog[i+1]*wz[i+1]=  
        (vy[i]+Bcog[i]*wz[i])*cos(thet  
        +vx[i]*sin(theta[i]);  
end for;
```

...





# Conclusions



# Conclusions & Future work

- HCT seems to come on to the roads in EU soon. Already today in Finland!
- Assessment can be arranged based on PBS.
  - Two cooperating assessment tools in Sweden (Finland involved in same project.):
    - LBK (launched)
    - Open PBS, “experiment version” launched:
      - “Assessment front-end”: at web
      - “R&D fronte-end”: at github at web
      - “Open” means anyone is welcome to try it and contribute
- For sure, other similar tools are developed.
  - E.g. the “framework≈tool” within Karel Kural’s PhD thesis work presented later today.



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**Thanks for your attention.  
Questions?**